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APPLICATION OF THE DUTCH METHOD FOR ESTIMATING
STORM-INDUCED DUNE EROSION(U) COASTAL ENGINEERING
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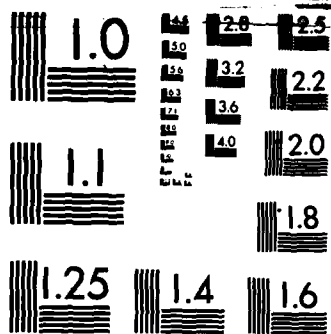
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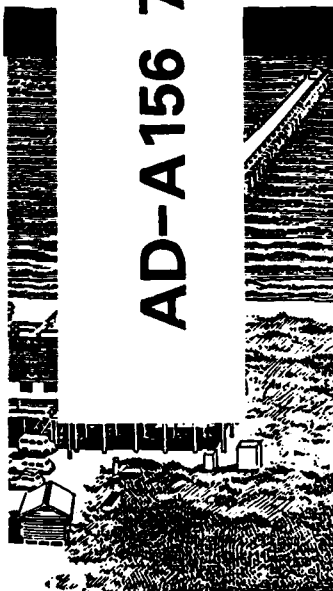


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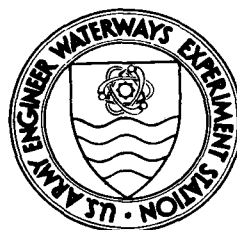
APPLICATION OF THE DUTCH METHOD FOR ESTIMATING STORM-INDUCED DUNE EROSION

by

Francis E. Sargent, William A. Birkemeier

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20. ABSTRACT (Continued).

and sediment size, and that the amount of material eroded will equal the deposition (i.e., cross-shore transport). The method has been verified for the Dutch coast based on both field measurements and laboratory experiments. An evaluation using a limited amount of data for the Atlantic and Gulf coasts of the United States found quantitative agreement with the method, justifying its application to storm conditions in the United States. This report discusses the method and identifies its inherent limitations. The procedure may be solved graphically or by using the included FORTRAN computer program.

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PREFACE

This report presents an easy-to-use procedure recently developed by the Dutch for predicting dune and beach erosion under large storm surge conditions. The report was prepared as part of the Storm Erosion Studies Work Unit 31467, Shore Protection and Restoration Program of the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES).

This report was prepared by Messrs. Francis E. Sargent and William A. Birkemeier, Hydraulic Engineers, under the direct supervision of Mr. Curt Mason, Chief, Field Research Facility, and Dr. James R. Houston, Chief, Research Division, CERC. Dr. Robert W. Whalin was Chief of CERC.

COL Robert C. Lee, CE, was Commander and Director of WES during the publication of this report. Mr. Fred R. Brown was Technical Director.



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APPLICATION OF THE DUTCH METHOD FOR ESTIMATING
STORM-INDUCED DUNE EROSION

PART I: INTRODUCTION

1. When a storm generates large wave and surge conditions, changes in the beach topography and nearshore bathymetry occur, often with significant beach and dune erosion. Until recently, little quantitative information on the prediction of beach and dune erosion existed to aid coastal engineers. The US Army Engineer Coastal Engineering Research Center's (CERC) Shore Protection Manual (1977) gives beach erosion quantities based only upon a qualitative description of a storm.

2. Based on the earlier work of Edelman (1968) and comprehensive model testing, Vellinga (1983) reported on an empirical method developed at the Delft Hydraulics Laboratory, Emmeloord, Netherlands, for estimating dune erosion for a given design storm. Though the method was designed for the Dutch coast, it provides reasonable results for the available data from events along the Gulf and Atlantic coasts of the United States, making it a useful tool for the design of dunes and beach fill projects and for identifying beaches vulnerable to storm damage. The purpose of this report is to describe the method and identify its limitations. The report includes an example problem using the method and an interactive computer program (FORTRAN 77) for applying it.

3. The three basic assumptions underlying the method are that (a) the shape of the poststorm profile is in equilibrium (the procedure does not include time dependency), (b) transport is in the offshore direction, and (c) the amount of material eroded must equal the amount deposited. There is no provision for handling longshore gains or losses to the profile. The concept is illustrated in Figure 1.

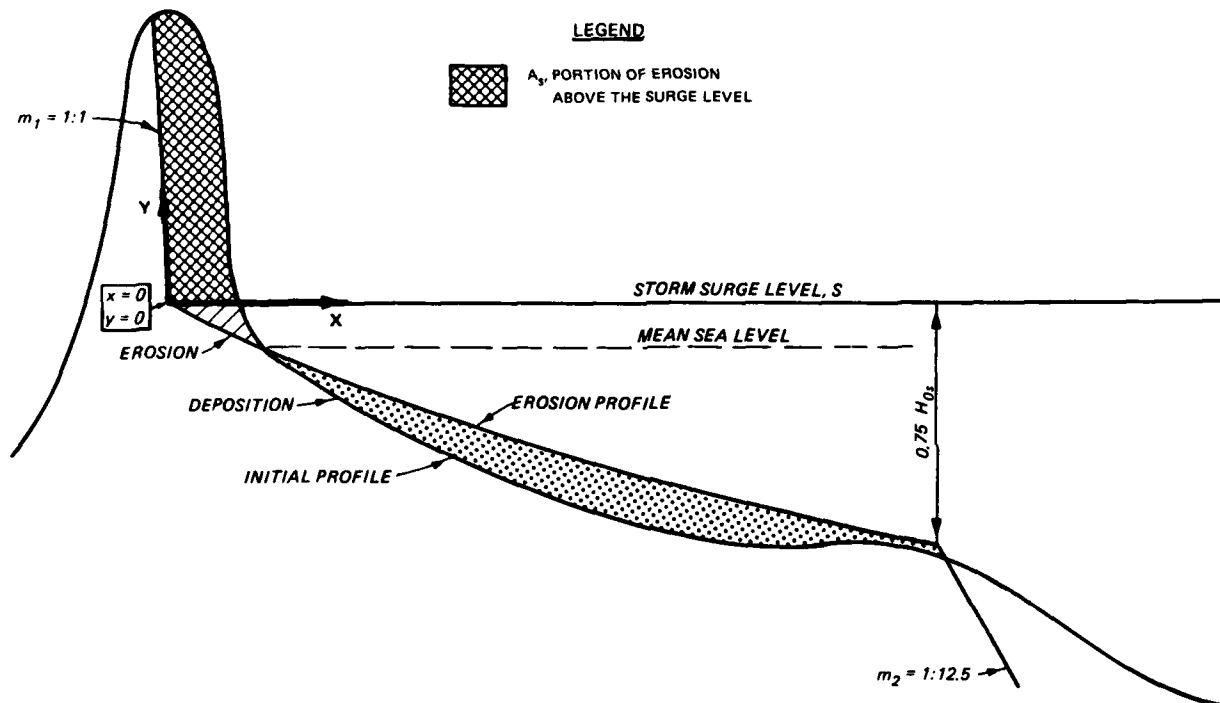


Figure 1. Definition sketch of prestorm and predicted poststorm profiles showing the resulting erosion and accretion zones (Vellinga 1983)

PART II: METHOD OF ANALYSIS

4. The method requires information about the shape of the prestorm profile (x_1 , y_1 , see Figure 1); the sediment fall velocity, w ; the significant deepwater wave height, H_{os} ; and the peak storm surge level, S .^{*} The prestorm profile should consist of field data taken offshore to a depth at least equal to $0.75 H_{os}$ below S (paragraph 6). If actual offshore data are unavailable, it may be possible to estimate the offshore portion of the profile using hydrographic charts or a predicted equilibrium shape (Dean 1977, Everts 1978). This will, however, decrease the accuracy of the method. The fall velocity, w , should correspond to the median sediment diameter, D_{50} , which is representative of the section of the profile that is expected to erode. Typically, D_{50} should be computed based on a composite of samples from the beach and dune zones. The fall velocity can be graphically determined from Figure 2 for a given water temperature and D_{50} .

5. The method is applicable within the varying range of wave steepness, $0.02 \leq H_{os}/L_o \leq 0.04$, where L_o is the significant deepwater wave length, and assumes a storm surge hydrograph similar to those occurring in the North Sea (Figure 3), with S defined as the summation of the astronomical high tide and the storm-induced water level relative to mean sea level (msl). This hydrograph is characterized by its height and short duration, and is similar to that produced by tropical storms along the coast of the United States. A procedure recommended by Vellinga (1983) for modifying the results for longer duration storm surges is discussed in paragraph 14. Ideally, both S and the wave height should be measured outside the breaker zone and the corresponding deepwater wave height, H_{os} , should be computed. Estimates of H_{os} and S could also be obtained from historical data, statistical analysis (Van de Graaff 1983), or numerical modeling of the storm conditions.

* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix B).

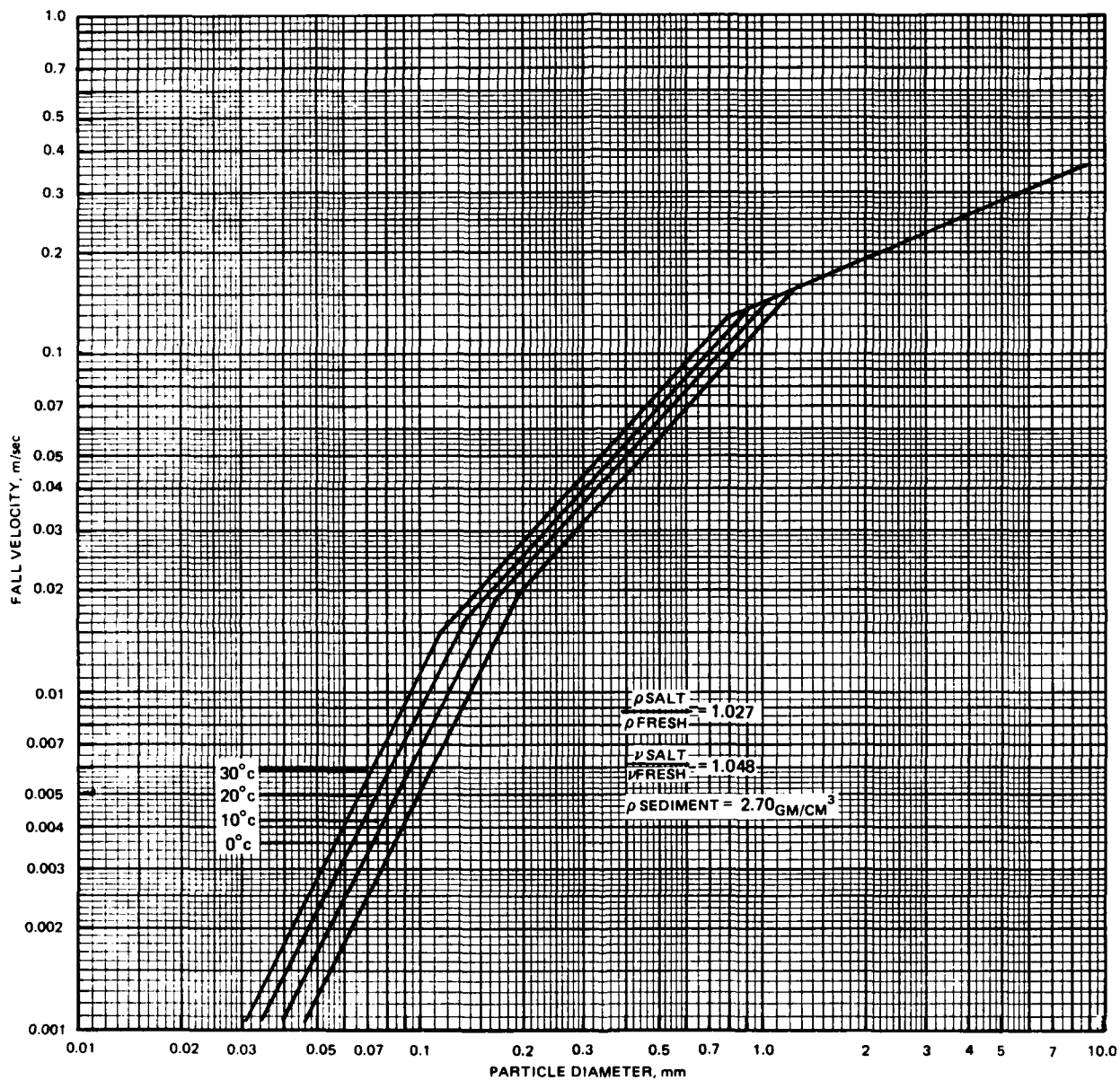


Figure 2. Fall velocity, w , as a function of the median particle size, D_{50} , and the water temperature, t . Curves obtained from selected ratios of saltwater to freshwater density, saltwater to freshwater viscosity, and a sediment density characteristic of quartz sand (Hallermeier 1981)

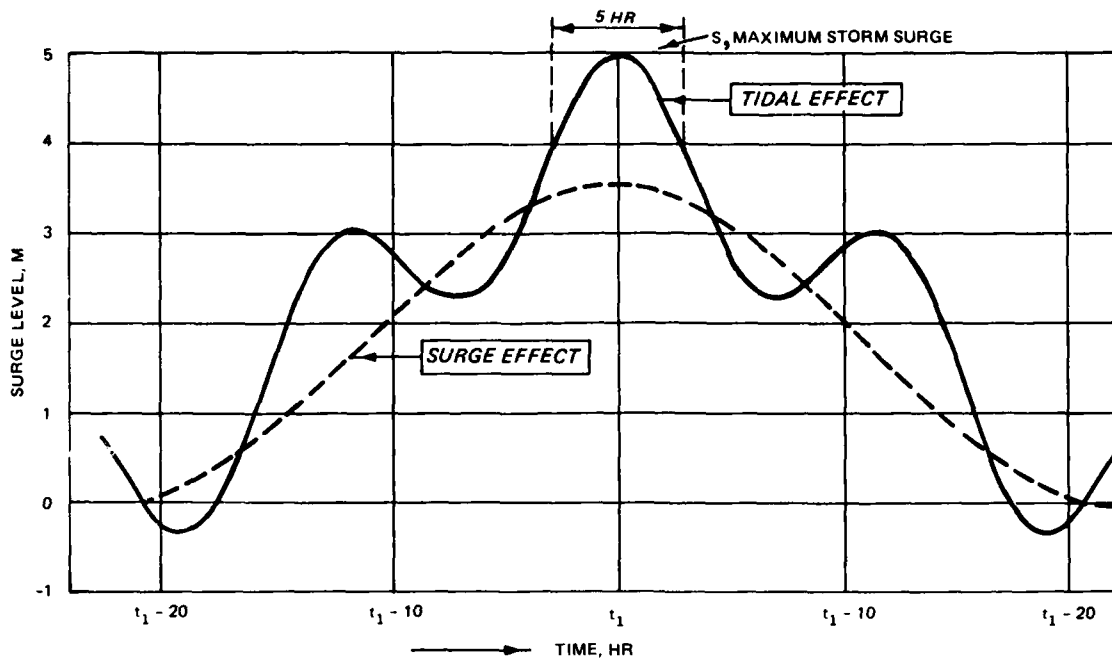


Figure 3. Typical time history of North Sea storm surge, with a return period of 10,000 years (Vellinga 1983)

6. Once H_{os} , S , and w have been determined, the shape of the poststorm profile can be obtained using the following equation:

$$y = \frac{2.0 - 0.47 \left[x \left(\frac{7.6}{H_{os}} \right)^{1.28} \left(\frac{w}{0.0268} \right)^{0.56} + 18 \right]^{0.5}}{\left(\frac{7.6}{H_{os}} \right)} \quad (1)$$

where x , y , and H_{os} are in meters and w is in m/sec. The profile defined by Equation 1 terminates offshore at

$$x = 250 \left(\frac{H_{os}}{7.6} \right)^{1.28} \left(\frac{0.0268}{w} \right)^{0.56} \quad (2)$$

which, substituting into Equation 1, yields

$$y = 0.75 H_{os} \quad (3)$$

Constant slopes are used to terminate the profile at the shoreward end (m_1 at $x = y = 0$) and seaward end (m_2) of Equation 1 and are defined as

$$m_1 = -1:1 \quad (4)$$

$$m_2 = -1:12.5 \quad (5)$$

Use of this steep poststorm dune face m_1 is consistent with field observations, and m_2 is arbitrarily fixed in agreement with model tests.

7. Once the poststorm profile is obtained, its position relative to the prestorm profile is determined by horizontally shifting the origin ($x = 0$, $y = 0$) along S until the erosion area A_e equals the deposition area. Then A_e , the gross area change A_g (equal to $2A_e$ since erosion is equal to deposition), the erosion area above the surge level A_s , and the horizontal dune recession R can be found using either the graphical or computational means described in Part VI.

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PART VIII: SUMMARY

22. An empirical model, developed using data from the field and from an extensive series of two-dimensional large- and small-scale movable bed model tests, has been proposed by the Dutch to estimate dune erosion for large storm surges. The model has been evaluated using less extreme field data from the United States Atlantic and Gulf coasts and should provide useful estimates of storm erosion. However, the user should be aware of the method's inherent limitations (Part V) and assumptions (Part I) when applying the model to site-specific conditions.

Since this is less than the maximum recommended change of 50 percent, A_s can be computed as

$$A_s = 1.4 \times 87.2 = 122.1 \text{ m}^3/\text{m}$$

which would be the required quantity of material above 3 m. Assuming the additional material ($34.9 \text{ m}^3/\text{m}$) has a constant elevation of +6 m, the additional dune recession is equal to

$$34.9/(6 - 3) = 11.7 \text{ m}$$

which places the dune crest at

$$-75.8 - 11.7 \text{ m} = -87.5 \text{ m}$$

a result identical to the one for the hurricane. Consequently, a dune crest width greater than 27.5 m is adequate for either the hurricane or storm conditions.

b. Given for northeaster:

$$S = 3.0 \text{ m}$$

$$H_{os} = 8.0 \text{ m}$$

$$D_{50} = 0.35 \text{ mm}$$

$$t = 2^\circ\text{C}$$

$$\text{duration} = 9 \text{ hours}$$

Solution: Since the width of the dune crest is unknown, extend it in the shoreward direction at a constant elevation of 6 m. From the computer program (or graphically), we find for the hurricane that $A_e = -155.5 \text{ m}^3/\text{m}$, A_s = the erosion quantity above 4 m as -79.4, and $R = -85.5 \text{ m}$, where R is defined as the poststorm position of the profile/surge level intercept. Then assuming the 1:1 slope of the dune face, the position of the dune crest ($y = +6 \text{ m}$) can be determined as

$$-85.5 - (6 - 4) = -87.5 \text{ m}$$

Since the prestorm dune crest position is at -50 m, a crest width of 27.5 m is required. Note that the value of A_s for the hurricane did not have to be duration adjusted since the storm duration (time the surge is within 1 m of peak surge, S) is equal to the North Sea storm duration of 5 hours.

21. For the northeaster, the following erosion estimates are $A_e = -145.6 \text{ m}^3/\text{m}$, A_s = the erosion quantity above 3 m = 87.2 m^3/m , and $R = -72.8 \text{ m}$. In following a treatment similar to that for the hurricane, we find the dune crest position to be

$$-72.8 - (6 - 3) = -75.8 \text{ m}$$

In order to adjust the volume and R to account for the 9-hour storm duration of the northeaster, use the procedure outlined in paragraph 14. Assuming (conservatively) a 10 percent additional change in volume per additional hour, then

$$10(9 - 5) = 40 \text{ percent}$$

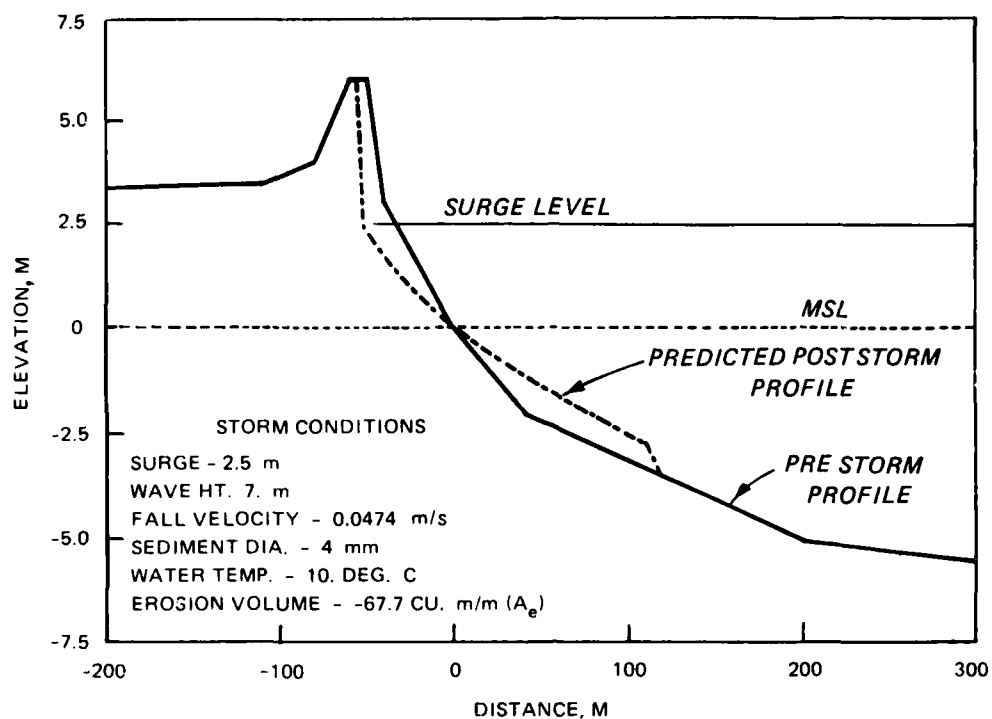


Figure 8. Equilibrium profile at Duck, N. C., with the predicted profile computed from the storm conditions listed

Example 2

20. Using the prestorm profile of example 1 and the computer program in Appendix A, find the maximum A_s and the width of the dune crest required to prevent dune failure for the following conditions (this could also be solved graphically):

a. Given for hurricane:

$$S = 4.0 \text{ m}$$

$$H_{os} = 9.0 \text{ m}$$

$$D_{50} = 0.35 \text{ mm}$$

$$t = 27^\circ\text{C}$$

$$\text{duration} = 5 \text{ hours}$$

PART VII: EXAMPLE PROBLEMS

Example 1

19. Figure 8 shows the predicted erosion caused by a simulated storm passing CERC's Field Research Facility in Duck, N. C. The storm produced 7-m deepwater waves and a 2.5-m surge. Using the graphical technique, compute the erosion which will occur if the surge had been 2.7 m. (The computational solution to the problem shown in Figure 8 is included in Appendix A.)

Given: $H_{os} = 7.0$ m

$S = 2.7$ m

$D_{50} = 0.35$ mm

$t = 25^\circ\text{C}$

Prestorm Profile (m)										
i	1	2	3	4	5	6	7	8	9	10
x_i	-500	-110	-80	-60	-50	-40	0	40	200	1200
y_i	3	3.5	4	6	6	3	0	-2	-5	-10

Solution:

- a. Given $D_{50} = 0.35$ mm , $t = 25^\circ\text{C}$, use Figure 2 to determine $w = 0.0474$ m/s .
- b. Plot the prestorm profile on graph paper. Compute the poststorm profile using Equations 1-5 and plot on tracing paper. (Or, since w and H_{os} are the same as in Figure 8, both profiles can be traced, as poststorm shape is independent of S .)
- c. Position poststorm profile at 2.7 m on the prestorm profile and slide it horizontally until the erosion and accretion areas between the two profiles balance.
- d. Once the areas balance, compute $A_e = -78$ m³/m and $A_s = -44$ m³/m by planimeter or by counting graph paper squares.
- e. Once plotted, the shift of the surge level contour can also be determined as -19.9 m.

PART VI: GRAPHICAL AND COMPUTATIONAL PROCEDURES

17. The simplicity of the model permits a graphical solution of the method. An example is given in Part VII. The procedure consists of

- a. For given values of H_{os} and w (obtained from Figure 2), construct a template of the predicted poststorm profile using Equations 1-5.
- b. Position the predicted dune toe ($x = y = 0$) of the template at the surge level intercept of the prestorm profile. Slide the template horizontally shoreward until the erosion area appears to equal the accretion area.
- c. Using a planimeter (or other method), find the erosion (-) and accretion (+) areas. Repeat the procedure, sliding the template right or left until the areas balance within acceptable limits (e.g. erosion area = accretion area \pm 5 percent).

18. An interactive computer program written in FORTRAN 77 is included in Appendix A along with instructions and a sample run. The computer program has several features to aid the interactive user including

- a. Computation of w , when the user supplies D_{50} and t (Figure 2).
- b. Use of English or metric system of measurement.
- c. Multiple interactive runs on the same profile, changing S , H_{os} , and w as desired.
- d. Output of erosion quantities to the user's terminal for immediate use.
- e. Error detection of input data, failure of convergence on a solution, or computation of nonvalid solution.

model solution will be valid if the elevation behind the dune is significantly higher (1 to 2 m) than the surge elevation, causing little or no overwash. Determination of the dune failure point for existing dune cross sections and design dune cross sections under various storm intensities can also be useful in designing protective dunes.

16. Another possible limitation which must be considered is the shape of the natural and predicted profiles. The method should work best for profiles that are similar to the Dutch ones used to develop the model (Figure 1). It may not work on profiles which deviate significantly from the typical Dutch profile. This problem was encountered first on a beach with a very flat offshore zone which covered a layer of peat. For this particular locality, the profile shape predicted by Equation 1 was too steep and always fell below the actual profile in the offshore region where deposition (not erosion) was expected. Similar problems may occur when the procedure is applied to a design beach, berm, or dune cross section which may be significantly different from the natural profile shape.

PART V: LIMITATIONS OF THE METHOD

13. The method assumes that all transport is in an offshore direction, that there is sufficient material to erode, and that the poststorm shape is in equilibrium. While these assumptions are probably acceptable for a single large event, over the long term (or where there are gradients in longshore transport) they may not be valid. For instance, as a result of the equilibrium assumption, for any additional erosion to occur following a storm, a larger storm must occur. In reality, a minor storm or several minor storms may cause the same amount of change as predicted for the larger event. Therefore, the engineer should be aware of long-term erosion trends and use the method with care in areas with known gradients in long-shore transport (near inlets, rivers, man-made or natural barriers, etc.). Similarly, the method should not be applied to beaches without dunes or beaches with seawalls.

14. Another assumption of the model is that the storm surge hydrograph should be similar to that shown in Figure 3. Although there is reasonable agreement between the model data and the United States data (Figure 5), the model appears to work best for large surge events (i.e., large A_s , Figure 4) since it was derived from experimental and field data with S greater than 3 m. The assumed duration of the surge peak (Figure 3) is similar to that of hurricanes occurring along the United States coast, but can be significantly shorter than that produced by a "northeaster." Based on large scale laboratory tests, Vellinga (1983) suggests increasing the erosion quantity A_s 5 to 10 percent for each additional hour of storm duration (maximum additional change not to exceed 50 percent of A_s). Storm duration is defined as the amount of time the surge level is within 1 m of S , minus the duration of the North Sea hydrograph (Figure 3) under the same criteria (5 hours). Note that this adjustment should be used as an upper estimate for erosional losses and may, in fact, be reduced by other factors such as offshore formations (paragraph 12). For example, although some of the data shown in Figure 5 should have been duration adjusted, a better agreement was obtained using adjusted values.

15. Model results may become questionable at the point of "dune failure," when the poststorm profile slope m_1 intercepts the prestorm profile landward of the dune crest. The possibility of overwash and shoreward movement of sand is not taken into account in the present model. Of course, the

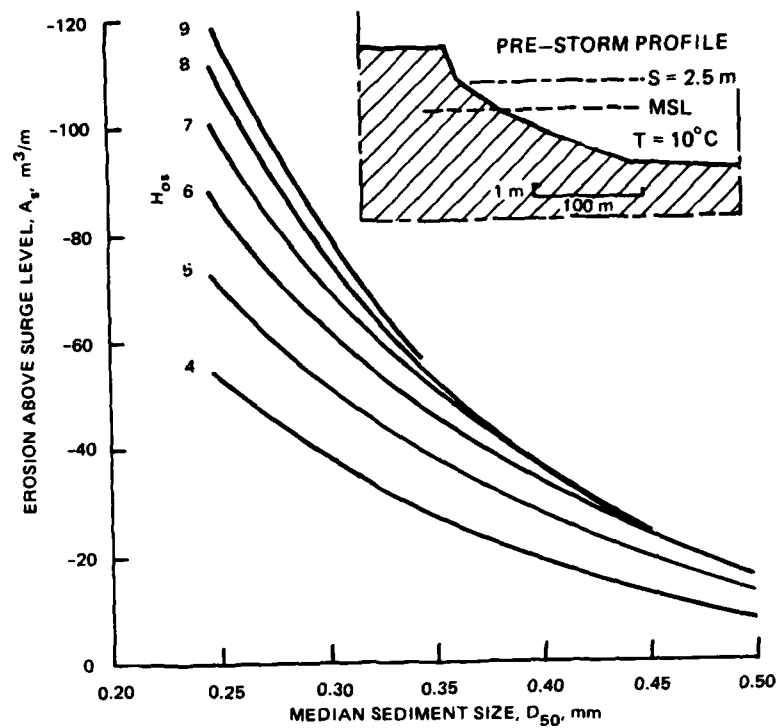


Figure 6. Erosion above surge level A_s as compared to the median sediment size D_{50} and the significant "deepwater" wave height H_{os} for the conditions shown

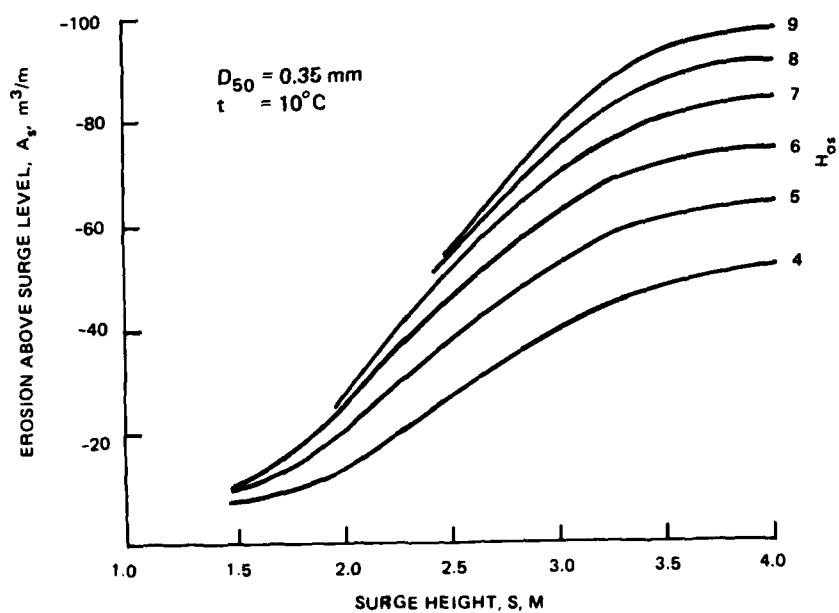


Figure 7. Erosion above surge level as compared to A_s surge level S and the significant deepwater wave height H_{os} , for the conditions shown

PART IV: SENSITIVITY OF THE METHOD

11. The explicit termination of the poststorm profile (m_1, m_2) and the arbitrary nature of the prestorm profile (dune shape, barred profile, etc.) make it difficult to quantitatively demonstrate how A_e (or A_s) changes with changes in H_{os} , S , or w . Vellinga (1983) presents a set of experiments showing the effect of several factors on A_s . He found that A_s was proportional to H_{os} , S , and the dune height, and that the trends predicted by the model agreed with the experimental data. Using several profile shapes and varying H_{os} , S , and w , qualitative estimates on the model's variability were obtained using the FORTRAN program given in Appendix A. In general, A_e and A_s vary directly with H_{os} and S , and are inversely proportional to w . These trends are shown in Figures 6 and 7 for a representative profile shape. Depending on the profile shape, small changes (10 percent) in H_{os} , S , or w can result in either large (greater than 30 percent) or small changes in A_e (and A_s). This points to the equal importance of H_{os} , S , and w in the modeling of dune erosion (although H_{os} and S are implicitly coupled). The water temperature t , required in determining w , can be very important in determining A_e , particularly from summer to winter when a change in t from 25°C to 5°C can cause A_e to increase by 70 percent.

12. Vellinga (1983) also indicated that the method is sensitive to the presence of an offshore bar and trough. He found from a series of model tests that when offshore bars were present, the model overpredicted A_s by 28 percent compared with 9 percent overprediction for similar experiments without offshore formations. This discrepancy may result from dissipation of incident wave energy by the bar. Because of the model's sensitivity to offshore features, knowledge of the typical bar and trough formations in a particular study area may help in interpreting the dune erosion estimates.

of the prestorm and poststorm offshore profile shape, wave height, storm surge and sediment size.

10. Since above surge level changes (A_s) were small and similar in magnitude to the models' accuracy (σ_{A_s}), values of A_{msl} [the change above mean sea level (msl)] have been plotted. Values of A_{msl} have not been adjusted for duration (see paragraph 14). Even for these relatively low quantities, the model produces reasonable estimates of erosion which are within the accuracy given in Equation 6. Predicted poststorm profile shapes were not usually in good agreement with actual poststorm profile shapes. Possible reasons for this could be the low magnitude of the surge levels, the use of assumed offshore data for some points, and the timing of the surveys (some of the data, particularly data from Westhampton, showed evidence of poststorm recovery). The data in Figure 3 suggest lower bounds for the storm surge and wave height of $S = 1.5$ m and $H_{os} = 3.5$ m. At values higher than these, there is better agreement between predicted and actual changes. At lower values, erosion is not necessarily universal, and some profiles on a given beach experience accretion.

The method also reasonably predicted changes ($S = 2.4$ m) in Florida (Hughes and Chiu 1981) caused by Hurricane Eloise.*

9. To further confirm the method, historic CERC data from United States' beaches for three storms were analyzed and are presented for a number of profile lines in Figure 5, along with the Hurricane Eloise data of Hughes

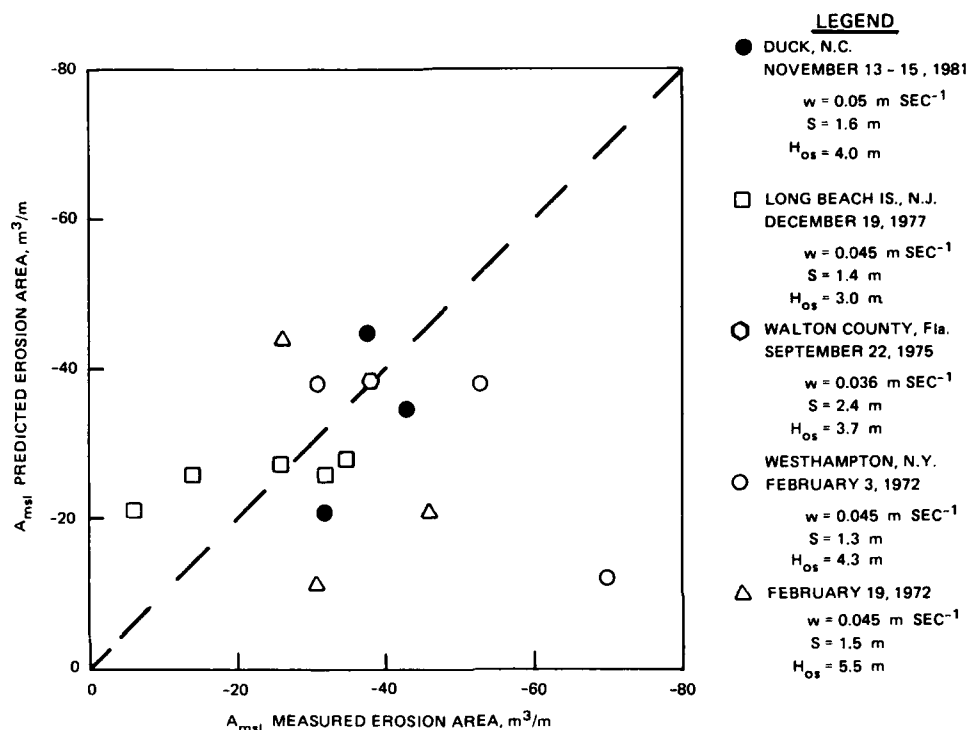


Figure 5. Comparison of predicted erosion A_{msl} and measured erosion for US Atlantic and Gulf coast data

and Chiu (1981). Profile data for the two February 1972 storms at Westhampton, N. Y., were from DeWall (1979) using hindcasted wave data and a fitted offshore slope. The storm surge was measured by a tide gage at Sandy Hook, N. J. Data from Long Beach Island, N. J., including surge data from Atlantic City, N. J. and wave gage data from near Sandy Hook, N. J., were reported by Birkemeier (1979). The offshore portion of the profiles were fitted using data from Everts (1978) and Dean (1977). Data from Duck, N. C., were collected near CERC's Field Research Facility and include detailed measurements

* Personal communication from Pier Vellinga, Subject: "Verification of Predictive Computational Model for Beach and Dune Erosion During Storm Surges - Verification for Field Data of Dune Erosion Caused by Hurricane Eloise at Walton County in Florida, September 1975," February 1983.

PART III: MODEL EVALUATION

8. Because of the general lack of extreme event profile data, the model is primarily based on an extensive series of small- and large-scale model tests. Results from these experiments compared with results from the predictive model are reported in Vellinga (1978, 1982, 1983) and are shown in Figure 4 for A_s . Figure 4 also includes field data from a storm surge event

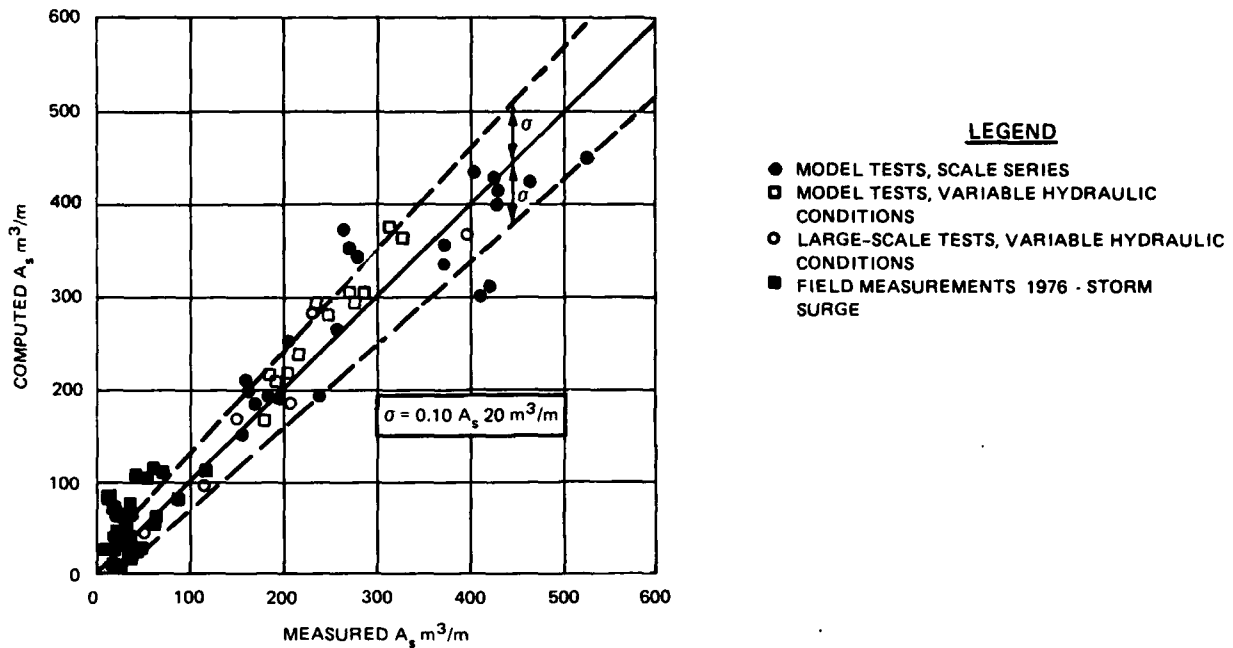


Figure 4. Comparison of predicted dune erosion A_s and measured dune erosion (Vellinga 1983)

($S = 3.0 \text{ m}$) that occurred on the coast of the Netherlands in 1976. The field and experimental data are in good agreement with the predicted erosion quantities, and poststorm surveys following a 1953 Dutch storm surge ($S = 3.9 \text{ m}$) confirm the shape of the predicted poststorm profile. Using statistical analysis of the data, Vellinga (1983) specifies the standard deviation of the prediction (shown as dashed lines in Figure 4) as

$$\sigma_{A_s} = (0.10 A_s + 20) \text{ m}^3/\text{m} \quad (6)$$

APPENDIX A: FORTRAN DUNE EROSION PROGRAM

Explanation of Program

1. A listing of "DUNE," the FORTRAN 77 dune erosion program, is included here, preceded by an interactive example run. This 700-line program has been adequately documented throughout with comment cards to aid users in modifying and understanding the program. The program first requests interactive input of the prestorm profile shape, sediment characteristics, and storm conditions. It also asks for the entry of two datums: one to define the surge height and one for use in volume computations. Once all required inputs have been entered, the program determines the poststorm profile shape, computes the location of the poststorm profile using a modified secant method, and computes the area changes (A_e , A_s). If the duration of the storm surge exceeds 5 hours, the program computes an adjusted estimate of the erosion using the procedure described in paragraph 14 of the main text. Program output is returned to both the user's terminal and a local file (FORTRAN Unit 14) for later printing.

2. All interactive input is from the user's terminal (FORTRAN Unit 5). User input in the example follows the input prompt "?". This may differ (or be a blank) on different computer systems. Required input data are entered in free format with multiple entries separated by blanks (as in the example) or by commas. "Yes" or "no" questions require either a Y or an N response. Program execution may be terminated at any time by entering a carriage return after the input prompt (signaling an End-of-File on input).

3. The user is first asked to label his data with the following:

- a. Locality code: 2-character beach identifier
- b. Profile number: range or line number
- c. Survey number: repetitive survey number
- d. Date: the date of the survey (YYMMDD)

The user is then asked if the computations and data entry are to be done in English units (a Y response) or metric (an N response). Units must be consistent throughout with the exception of the sediment size which must be entered in millimeters.

4. The user must next enter the survey data which define the prestorm profile shape. The points are entered, one per line, with distance (X_1) followed by elevation (Y_1). Up to 110 points may be entered and they should be entered in ascending order (the program checks for this). Data should be

entered accurately since the program has no provision to interactively list or correct entered data. Enter a carriage return to terminate survey data entry.

5. The following information is requested to begin the computation (a similar listing is also available interactively):

- a. Surge datum: Vertical datum, relative to the profile datum used to define the relative positioning of the surge height in m (or ft).
- b. Surge height: Height of the storm surge above the surge datum in m (or ft).
- c. Wave height: Significant wave height H_{os} in m (or ft).
- d. Change datum: Vertical datum, relative to the profile data, above which the erosion quantity, A_s , will be computed.
- e. Storm duration: The duration in hours that the surge level is within 1 m (3.3 ft) of the peak surge height. This is optional. Enter a zero if the duration is unknown.

6. The use of two datums in the calculations allows considerable flexibility in the input data. The surge datum allows the surge height to be entered relative to a datum other than the datum of the profile data. For example, profile data are often measured relative to mean sea level ($msl = 0$) while tide data may be measured relative to mean low water ($mlw = 0$). In this case, using for surge height the actual tide data, enter for the surge datum the difference between msl and mlw (which should be a negative value). The change datum defines the lower boundary for the computation of A_s . Normally, A_s is computed relative to the surge level. (To do so, enter the height of the surge, relative to the profile datum.) It is also possible to compute a modified value of A_s relative to any elevation. For instance, to compute the change above msl , enter a zero for the change datum (if the profile data are relative to msl).

7. The sediment fall velocity may be entered directly or computed for a given sediment size and water temperature. The fall velocity should be entered in m/sec (or ft/sec), the median sediment size in mm, and the temperature in degrees C (or degrees F).

8. Following data entry, the program computes and displays at the terminal:

- a. The total erosion area (A_e) - the volume of the total eroded area, regardless of datum.

- b. The above datum change (A_s) - the volume change above the change datum.
- c. The horizontal shift of the change datum intercept.
- d. The position, relative to the profile data, of the poststorm surge level intercept.
- e. An adjusted value of A_s which accounts for storm duration (if the duration exceeded 5 hours).

Note that in determining the adjusted value of A_s , the program does not check to see if sufficient additional material actually exists. Use the adjusted amount only as an indicator of the possible erosion. In addition to the terminal output, a more complete summary of the run is written to FORTRAN Unit 14 for later routing to a printer. The Unit 14 output includes a listing of all input and output data and a listing of the coordinates which define the predicted poststorm profile shape (unadjusted for the storm duration).

9. Following each run, the user is asked if another run is desired. Since the profile data need not be re-entered, multiple runs can be used to determine the effect of varying any of the parameters.

10. There are instances when the program will be unable to compute a solution. These include the following:

- a. Input errors resulting from incorrect entry of the input data or use of illegal values.
- b. A surge height that is higher than the highest point on the profile.
- c. A change datum that is higher or lower than the data defined by the predicted profile.
- d. A predicted profile shape that falls either above or below the prestorm shape in a zone where the opposite should occur. For example, the predicted profile should fall above the prestorm profile in the offshore zone and below the prestorm on the beach. If this does not occur, the procedure will not work.
- e. If the prestorm profile has insufficient beach or dune width for the procedure, the predicted profile will fall landward of all the prestorm data points and an incorrect solution will result.

The program prints an error message when each of these (or variations of them) are encountered. When possible, the program will still compute results but the user should use them with care. The best way to identify the effect of an error is to plot the prestorm and predicted profile data to see if a reasonable solution was obtained.

11. Should the program fail to converge on a solution, it may be useful to examine the sequence of iterations which occurred. These are printed out in reverse order (from the most recent iteration) on Unit 14 after each run. The top line is the iterations required to determine the horizontal shift of the profile (relative to the datum of the profile data) and the second line is the difference between the erosion and accretion volumes (which should be nearly equal to zero for the most recent iteration).

12. As written, the three subroutines to program DUNE are compatible with the Interactive Survey Reduction Program (ISRP) developed by Birkemeier (1984).^{*} With minor modifications to the ISRP calling and plotting routines (which has been done), it is possible to interactively generate and plot the actual and pre- and poststorm profiles, together with the program's predicted profile (Figure 8). In addition, ISRP has much more powerful survey data entry, modification, and correction capability than program DUNE. Corps of Engineers users interested in either DUNE or ISRP should contact the Coastal Engineering Research Center.

^{*} References are located at the end of the main text.

INTERACTIVE PROGRAM EXAMPLE

DUNE - A PROGRAM TO ESTIMATE STORM INDUCED DUNE EROSION.
WRITTEN BY FRANCIS SARGENT, CERC, 1983.

THIS PROGRAM USES A PROCEDURE DEVELOPED BY VELLINGA
OF THE DELFT HYDRAULICS LABORATORY, THE NETHERLANDS.

NOTE - A CARRIAGE RETURN AT ANY TIME WILL
TERMINATE PROGRAM EXECUTION

ENTER 2 CHARACTER LOCATION CODE OF PRE-STORM PROFILE

? NB

ENTER PROFILE AND SURVEY NUMBERS

? 100 34

ENTER SURVEY DATE (YYMMDD)

? 840425

LENGTH SCALE IN FEET (ELSE METERS)? - Y OR N

? N

ENTER SURVEY DATA - DISTANCE THEN ELEVATION
ONE POINT PER LINE, ASCENDING BY DISTANCE

TERMINATE DATA ENTRY WITH A CARRIAGE RETURN

? -500 3

? -110 3.5

? -80 4

? -300 4

LAST POINT NOT ASCENDING, PLEASE RE-ENTER

? -60 6

? -50 6

? -40 3

? 0 0

? 40 -2

? 200 -5

? 1200 -10

?

← ERROR MESSAGE FOR
POINT ENTERED OUT OF
ORDER

← CARRIAGE RETURN ENTERED TERMINATING DATA ENTRY

DO YOU WANT TO SEE A DESCRIPTION OF THE
INPUT AND OUTPUT VARIABLES?

? N

ENTER - SURGE DATUM, SURGE HEIGHT, WAVE HEIGHT,
AND CHANGE DATUM (IN M)

← ENTER A "Y" TO GET A
DESCRIPTION OF VARIABLES

? 0 2.5 7.0 2.5

ENTER HOURS STORM SURGE EXCEEDED 1.50 M (OR ENTER 0)

? 8

COMPUTE PARTICLE FALL VELOCITY GIVEN DIAMETER? - Y OR N

? Y

ENTER - MEDIAN SAND SIZE (MM) AND WATER TEMP. (DEG C)

? .40.10

FALL VELOCITY = .0474 M /SEC

TOTAL EROSION (AE) = -67.7 M³/ M

ABOVE DATUM CHANGE (AS) = -36.1 M³/ M

HORIZONTAL SHIFT OF CHANGE DATUM = -18.2 M

POSITION OF SURGE LEVEL = -52.4 M

ESTIMATED EROSION ADJUSTED FOR DURATION
(IF SUFFICIENT MATERIAL EXISTS)

EROSION ABOVE CHANGE DATUM (AS) = FROM -41.56 TO -46.98 M³/M

OUTPUT PRINTED TO UNIT 14

DUTCH STORM EROSION PREDICTION

LOCATION NB PROFILE NO. 100
SURVEY NO. 34 DATE (YYMMDD) 840425

*** INPUT ***

PRE-STORM PROFILE

POINT NUMBER	DISTANCE M	ELEVATION M
1	-500.0	3.00
2	-110.0	3.50
3	-80.0	4.00
4	-60.0	6.00
5	-50.0	6.00
6	-40.0	3.00
7	0.0	0.00
8	40.0	-2.00
9	200.0	-5.00
10	1200.0	-10.00

SURGE HEIGHT = 2.50 M
SURGE DURATION = 8.00 HRS
SIGNIFICANT WAVE HEIGHT = 7.00 M
MEDIAN SEDIMENT DIAMETER = .40 MM
WATER TEMPERATURE = 10.0 DEG C
COMPUTED FALL VELOCITY = .0474 M /SEC
SURGE DATUM = 0.00 M
CHANGE DATUM = 2.50 M

*** RESULTS ***

TOTAL EROSION (AE) = -67.7 M³/M
 ABOVE DATUM CHANGE (AS) = -36.1 M³/M
 HORIZONTAL SHIFT OF CHANGE DATUM = -18.2 M
 POSITION OF SURGE LEVEL = -52.4 M

ESTIMATED EROSION ADJUSTED FOR DURATION
 (IF SUFFICIENT MATERIAL EXISTS)

EROSION ABOVE CHANGE DATUM (AS) = FROM -41.56 TO -46.98 M³/M

POST-STORM PROFILE

DISTANCE M	ELEVATION M
---------------	----------------

-55.7	6.00
-52.4	2.50
-50.0	2.32
-40.0	1.70
-30.0	1.20
-20.0	.77
-10.0	.39
0.0	.04
10.0	-.28
20.0	-.59
30.0	-.87
40.0	-1.14
50.0	-1.40
60.0	-1.64
70.0	-1.98
80.0	-2.11
90.0	-2.33
100.0	-2.54
110.0	-2.75
111.0	-2.77
120.2	-3.50

← THIS IS X-COORDINATE
 OF POSTSTORM DUNE CREST

SURGE POSITION AND NET AREA ITERATIONS IN
 REVERSE ORDER (FROM LAST TO FIRST).

-52.433	-52.438	-53.761	-49.676
.000	.045	12.603	-26.298

PROGRAM DUNE

```

PROGRAM DUNE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE14)
C
C PROGRAM 'PMAIN' USED TO ENTER PROFILE DATA AND CALL
C SUBROUTINE 'PREDICT' WHEN USED AS A STAND-ALONE PROGRAM.
C
  INTEGER IP, IDATEP, IPROP, NINC, IP1
  CHARACTER*1 ANSWER, REPLY
  REAL P
  COMMON /DATA/X(110),Y(110),Z(110),NPOINTS,PORT(110),CONSL(110),IU
  COMMON /DLK/IDATE,ITIME,IPROP,ILOC,ISUR,DIST,IUNIT
  COMMON /PRDCT/P(110,3),IP,IDATEP,IPROP,NINC,IP1
  COMMON /FALVEL/PDIA,CTEMP,FALLVEL,SURGE,WAVEHT,TEMP,BAREA
  DATA M,F/2HM,2HFT/
C
C FIRST WRITE PROGRAM INTRO
C
  WRITE(6,900)
900  FORMAT(//,1X,"DUNE - A PROGRAM TO ESTIMATE STORM INDUCED",
  $1X,"DUNE EROSION.",/.1X," WRITTEN BY FRANCIS SARGENT.",
  $" CERC, 1983.",//
  $1X,"THIS PROGRAM USES A PROCEDURE DEVELOPED BY VELLINGA",/,
  $1X,"OF THE DELFT HYDRAULICS LABORATORY, THE NETHERLANDS.",//,
  $1X,"NOTE - A CARRIAGE RETURN AT ANY TIME WILL",/
  $1X,"TERMINATE PROGRAM EXECUTION",//)
100  WRITE(6,1010)
      READ(5,1110,ERR=100,END=220)ILOC
      IP=0
C
C SET MAXIMUM NUMBER OF SURVEY POINTS ALLOWED. THIS
C MUST BE EQUAL OR LESS THAN THE ARRAY SIZE OF X AND Y ARRAYS
C
  NPOINTS=110
110  WRITE(6,1020)
      READ(5,*,ERR=110,END=220)IPROP,ISUR
115  WRITE(6,1025)
      READ(5,*,ERR=115,END=220)IDATE
120  WRITE(6,1050)
      READ(5,1100,ERR=120,END=220)ANSWER
      IF(ANSWER.EQ.'Y')THEN
        IUNIT=2HFT
      ELSE IF(ANSWER.EQ.'N')THEN
        IUNIT=2HM
      ELSE
        GOTO120
      END IF
140  WRITE(6,1040)
      DO 170 I=1,NPOINTS
145  READ(5,*,ERR=140,END=180)Y(I),Z(I)
      IF(I.EQ.1)GO TO 170
C
C CHECK TO BE SURE DISTANCES ARE ASCENDING
C
      IF(Y(I).GE.Y(I-1))GO TO 170
      WRITE(6,150)
150  FORMAT("LAST POINT NOT ASCENDING, PLEASE RE-ENTER")
      GO TO 145
160  WRITE(6,165)
165  FORMAT("INPUT ERROR,PLEASE RE-ENTER")
      GO TO 145
170  CONTINUE
C
C CLEAR END-OF-FILE FLAG BEFORE CONTINUING.
C
180  K7=EOF(5)
      NPOINTS=I-1
C
190  CALL PREDICT
C
200  WRITE(6,1030)
      READ(5,1100,ERR=200,END=220)ANSWER

```

```

      IF(ANSWER.EQ.'Y')THEN
250  WRITE(6,1060)
      READ(5,1100,ERR=210,END=220)ANSWER
      IF(ANSWER.EQ.'Y')GOTO100
      IF(ANSWER.EQ.'N')GOTO190
      GOTO210
    ELSE
      IF(ANSWER.NE.'N')GOTO200
    END IF
1010  FORMAT("ENTER 2 CHARACTER LOCATION CODE OF PRE-STORM PROFILE")
1020  FORMAT("ENTER PROFILE AND SURVEY NUMBERS")
1025  FORMAT("ENTER SURVEY DATE (YYMMDD)")
1030  FORMAT("DO YOU WANT ANOTHER RUN? - Y OR N")
1040  FORMAT("ENTER SURVEY DATA - DISTANCE THEN ELEVATION",/,
$      "ONE POINT PER LINE, ASCENDING BY DISTANCE",/,
$      //"TERMINATE DATA ENTRY WITH A CARRIAGE RETURN",//)
1050  FORMAT("LENGTH SCALE IN FEET (ELSE METERS)? - Y OR N")
1060  FORMAT("NEW PROFILE? - Y OR N")
1100  FORMAT(A1)
1110  FORMAT(A2)
220  STOP
    END
C
C*****
C
C      SUBROUTINE PREDICT
C
C      PREDICT - CERC FRF - BCS:FTN5 - F. E. SARGENT - 830609
C      PROFILE GIVEN A 'PRESTORM' PROFILE AND SEVERAL BULK PARAMETERS
C      OF THE STORM AND BEACH. THE PROGRAM FOLLOWS A METHOD PRESENTED
C      BY VELLINGA (1983). THE POSITIVE Y-DIRECTION IS OUTWARD
C      NORMAL AND THE POSITIVE Z-DIRECTION IS UPWARD. 'PREDICT' CAN BE
C      USED AS A STAND-ALONE PROGRAM WITH ITS CALLING PROGRAM 'PMAIN' OR
C      AS A SUBROUTINE TO PROGRAM 'ISRP' DEVELOPED BY BILL DIRKEMEIER AT
C      THE CERC FIELD RESEARCH FACILITY. PROGRAM CODING IS IN FORTRAN77.
C
C      REAL DZ1,DZ2,DY,SAREA,CW,CY,CZ,ZACT1,ZACT2,YACT1(13),YACT2,BAREA
C      REAL M1,M2,TAREA1,TAREA2,DAREA(13),T1,SURGE,WAVEHT,FALLVEL,DATUM
C      REAL P,YIT,ZEND,YEND,CAREA,SLOPE1,YC1,YC2,ZC1,ZC2,Y1,Z1,AREA(3),PR
C      REAL DY2,EAREA,C,C1,C2,C3,DATUM2,K1,K2,PDIA,TEMP,CTEMP,POS(2),T2
C      REAL SMIN,WMIN,FMIN,PMIN
C      INTEGER INDEX,INDEX1,INDEX2,IP,IDATEP,FLAG,NINC,IP1,I,J,K,L,M,N,ML
C      INTEGER ZSIGN1,ZSIGN2,IY,YS1,YS2,YE1,YE2,IRODE,ASIGN1,ASIGN2,IPROP
C      INTEGER FRMT,OPOUT,U
C      CHARACTER*2 U2,U4,REPLY*1,ANSWER*1
C
C      LABELED COMMON BLOCKS USED WITH PROGRAM 'ISRP'.
C
C      COMMON /DATA/X(110),Y(110),Z(110),NPOINTS,PORT(110),CONSL(110),IU
C      COMMON /BLK/IDATE,ITIME,IPROP,ILOC,ISUR,DIST,IUNIT
C      COMMON /PRDCT/P(110,3),IP,IDATEP,IPROP,NINC,IP1
C      COMMON /FALLVEL/PDIA,CTEMP,FALLVEL,SURGE,WAVEHT,TEMP,BAREA
C
C      GLOBAL CONSTANTS (NOT CHANGED ON SUBSEQUENT CALLS TO 'PREDICT')
C      NINC < OR = DIMENSION OF PROFILE ARRAYS IN LABELED COMMON 'DATA'
C      MAY OTHERWISE BE DEFINED IN A 'BLOCK DATA' STATEMENT.
C
C      DATA X1,K2,M1,M2,T1,T2,ML/.471405,.752266,-1.,-.08,.01,.01,13/
C      DATA SMIN,WMIN,PMIN,FMIN,OPOUT/3*.01,.001,0/
C      NINC=110
C      N=NINC-1
C
C      SET FLAGS FOR 'ISRP' PLOTTING ROUTINE 'IPL0T'.
C
C      IP=1
C      IDATEP=IDATE
C      IPROP=IPROP
C      U=IUNIT
C
C      USE APPROPRIATE UNITS (FEET OR METERS) FOR ANALYSIS.

```

```

      IF(IUNIT.EQ.2HM) THEN
      C=1.
      C1=1.
      C2=0.
      C3=2.
      U2=' M'
      U4=' C'
      ELSE
      C=.3048
      C1=.3556
      C2=32.
      C3=54.
      U2=' YD'
      U4=' F'
      END IF
100  CONTINUE
      IF(IPDZ.EQ.1)GO TO 102
C
C  DETERMINE IF AN EXPLANATION OF THE VARIABLES IS DESIRED?
C
C
      WRITE(6,1011)
1011 FORMAT(/,1X,"DO YOU WANT TO SEE A DESCRIPTION OF THE",/,
      $1X,"INPUT AND OUTPUT VARIABLES?")
      READ(5,1030,END=410,ERR=100)IREPLY
      IF(IREPLY.EQ.1HY)CALL EXPLAIN
      IPDZ=1
102  CONTINUE
C
C  REQUEST ENTRY OF SURGE AND WAVE HEIGHT PARAMETERS
C
C
      WRITE(6,1000) U
      READ(5,*,ERR=105,END=410)DATUM,SURGE,WAVEHT,DATUMZ
C
C  REQUEST STORM DURATION IN HOURS FOR LATER ADJUSTMENT
C  OF THE EROSION AMOUNTS (IF DURATION GT 5 HRS)
C
      S=SURGE-1./C
106  WRITE(6,107)S,U
107  FORMAT(1X,"ENTER HOURS STORM SURGE EXCEEDED",
      $F6.2,1X,A2," (OR ENTER 0)")
      READ(5,*,ERR=106,END=410)DUR
C
C  SUBTRACT DURATION OF NORTH SEA STORM
C
C
      DUR=DUR-5.
      IF(DUR.LT.0.)DUR=0.
C
C  COMPUTE FALL VELOCITY GIVEN MEDIAN PARTICLE DIAMETER (IN MM)
C  AND WATER TEMPERATURE. OTHERWISE INPUT FALL VELOCITY.
C
      WRITE(6,1020)
      READ(5,1030,ERR=100,END=410)REPLY
      IF(REPLY.EQ.'Y')THEN
110  WRITE(6,1010)U4
      READ(5,*,ERR=110,END=410)PDIA,TEMP
C
C  CONVERT TEMPERATURE TO DEG C (IF REQUIRED)
C
      CTEMP=C1*(TEMP-C2)
      IF(CTEMP.GE.0..AND.CTEMP.LE.40..AND.PDIA.GT.PMIN)GOTO120
      WRITE(6,1250)
      GOTO110
120  CALL SPEED
      FALLVEL=FALLVEL/C
      WRITE(6,123)FALLVEL,U
123  FORMAT(" FALL VELOCITY =",F7.4,1X,A2,"/SEC")
      ELSE IF(REPLY.EQ.'N')THEN
      PDIA=0.
130  WRITE(6,1015)

```

```

READ(5,*,ERR=130,END=410)FALLVEL
ELSE
GOTO100
END IF
IF (FALLVEL.GT.FMIN.AND.WAVEHT.GT.WMIN.AND.SURGE.GT.SMIN)GOTO140
WRITE(6,1240)
GOTO100
C
C
C INITIALIZE CONSTANTS AND FLAGS.
140 ASIGN1=-1
    ASIGN2=-1
    CH=(FALLVEL*C/0.0268)**.56
    CZ=7.6/(WAVEHT*C)
    CY=CZ**1.28*CH
    ZACT1=DATUM+SURGE
    IF(Z(NPOINTS).LT.ZACT1)GOTO150
    WRITE(6,1060)
    ASSIGN 1060 TO FRMT
    FLAG=2
    GOTO340
C
C
C INITIALIZE FIRST TWO 'GUESSES' OF POST-STORM PROFILE POSITION.
150 DO 160 I=NPOINTS,1,-1
    IF(Z(I).LT.ZACT1)GOTO160
    INDEX=I
    GOTO170
160 CONTINUE
    WRITE(6,1070)
    ASSIGN 1070 TO FRMT
    FLAG=2
    GOTO340
170 SLOPE=(Y(I)-Y(I+1))/(Z(I)-Z(I+1))
    YIT=(ZACT1-Z(I+1))*SLOPE+Y(I+1)
    YEND=250./(CY*C)
    YACT1(1)=YIT-YEND/10.
    YACT1(2)=YIT-YEND/8.
    ZEND=K2*WAVEHT
    ZACT2=ZACT1-ZEND
    CAREA=YEND*ZACT1+2.*YEND/(CZ*C)+(72.-2.*K1*(CY*C*YEND+18.))*1.5)/
    $ (3.*C*C*CZ*CY)
C
C
C LOOP INTERACTION STARTS HERE, USING A SECANT METHOD TECHNIQUE.
DO 270 J=1,ML
    FLAG=0
    YACT2=YACT1(J)+YEND
C
C
C LOCATE LOWER INDEX OF THE PRESTORM PROFILE AT THE LEFT END
    OF CURVED PORTION OF PREDICTED PROFILE.
C
C
C DO 190 I=INDEX+1,1,-1
    IF(Y(I).GT.YACT1(J))GOTO190
    SLOPEI=(Z(I)-Z(I+1))/(Y(I)-Y(I+1))
    IF(SLOPEI.LE.M1)GOTO190
    YCI=(M1*YACT1(J)-SLOPEI*Y(I+1)+Z(I+1)-ZACT1)/(M1-SLOPEI)
    IF(YCI.LT.Y(I))GOTO190
    INDEX=I+1
    IF(YCI.LE.YACT1(J))GOTO180
    YCI=YACT1(J)
    FLAG=1
180 ZCI=SLOPEI*(YCI-Y(I+1))+Z(I+1)
    GOTO200
190 CONTINUE
    WRITE(6,1080)
    ASSIGN 1080 TO FRMT
    FLAG=2
    GOTO340
C
C
C LOCATE UPPER INDEX OF THE PRESTORM PROFILE AT THE RIGHT END

```

```

C      OF CURVED PORTION OF PREDICTED PROFILE.
C
200  DO 220 I=INDEX,NPOINTS,1
      IF(Y(I).LT.YACT2)GOTO220
      SLOPE1=(Z(I)-Z(I-1))/(Y(I)-Y(I-1))
      IF(SLOPE1.LE.M2)GOTO220
      YC2=(M2*YACT2-SLOPE1*Y(I-1)+Z(I-1)-ZACT2)/(M2-SLOPE1)
      IF(YC2.GT.Y(I))GOTO220
      INDEX2=I-1
      IF(YC2.GE.YACT2)GOTO210
      YC2=YACT2
      FLAG=1
210  ZC2=SLOPE1*(YC2-Y(I-1))+Z(I-1)
      GOTO230
220  CONTINUE
      WRITE(6,1090)
      ASSIGN 1090 TO FRMT
      FLAG=2
      GOTO340

C
C      COMPUTE AREAS RELATIVE TO ZERO DATUM - PREDICTED AREA.
C
230  TAREA1=((ZC1+ZACT1)*(YACT1(J)-YC1)+(ZC2+ZACT2)*(YC2-YACT2))/2.
C
C      PROFILE AREA.
C
      TAREA1=TAREA1+CAREA
      IF(INDEX2.GE.INDEX1)THEN
        TAREA2=(ZC1+Z(INDEX1))*(Y(INDEX1)-YC1)
        IF(INDEX2.EQ.INDEX1)GOTO250
        DO 240 I=INDEX1,INDEX2-1
          TAREA2=TAREA2+(Z(I)+Z(I+1))*(Y(I+1)-Y(I))
240  TAREA2=(TAREA2+(Z(INDEX2)+ZC2)*(YC2-Y(INDEX2)))/2.
250  ELSE
        TAREA2=(ZC1+ZC2)*(YC2-YC1)/2.
      END IF

C
C      CHECK IF AREAS LESS THAN TOLCRANCE (OR FLAG IS EXECUTED).
C      EXIT IF SO. OTHERWISE COMPUTE NEW GUESS AND RECOMPUTE AREAS.
C      ITERATION PROCEDURE BASED ON STANDARD SECANT EXTRAPOLATION
C      TECHNIQUE WHEN NET AREAS (DAREA) ARE OF THE SAME SIGN.
C      WHEN NET AREAS ARE OF OPPOSITE SIGN PROGRAM SELECTS TWO
C      BOUNDING VALUES TO INTERPOLATE NEW PROFILE POSITION.
C
      DAREA(J)=TAREA2-TAREA1
      IF(ABS(DAREA(J)).LE.T1)GOTO280
      IF(DAREA(J).LT.0)THEN
        IF(ASIGN2.EQ.1)THEN
          IF(DAREA(J).GT.DAREA(J2))J2=J
        ELSE
          ASIGN2=1
          J2=J
        END IF
      ELSE
        IF(ASIGN1.EQ.1)THEN
          IF(DAREA(J).LT.DAREA(J1))J1=J
        ELSE
          ASIGN1=1
          J1=J
        END IF
      END IF
      IF(ASIGN1.EQ.1.AND.ASIGN2.EQ.1)THEN
        JN=J1
        JO=J2
      ELSE
        JN=J
        JO=J-1
      END IF
      IF(J.EQ.1.OR.J.EQ.ML)GOTO270
      SLOPE=(YACT1(JN)-YACT1(JO))/(DAREA(JN)-DAREA(JO))
      YACT1(J+1)=YACT1(JN)-DAREA(JN)*SLOPE

```

```

270  CONTINUE
    FLAG=3
    J=ML
C
C  COMPUTE ABSOLUTE AREA CHANGE AND CHANGE ABOVE AREA CHANGE
C  DATUM. ADDITIONAL CONVERGENCE CHECK BASED ON NET AREA CHANGE.
C  DISCRITIZE PRE/POST PROFILES BETWEEN THEIR INTERCEPTS.
C
280  P(1,1)=YC1
    P(1,2)=ZC1
    P(1,3)=ZC1
    IF(ABS(YACT1(J)-YC1).LT..0001)P(1,3)=ZACT1
    P(NINC,1)=YC2
    P(NINC,2)=ZC2
    P(NINC,3)=ZC2
    IF(ABS(YACT2-YC2).LT..0001)P(NINC,3)=ZACT2
C
C  COMPUTE DISTANCES AND PRE/POST STORM ELEVATIONS.
C
    L=INDEX1
    DY=YC2-YC1
    DO 300 I=2,N
    P(I,1)=YC1+DY*(I-1)/N
    IF(P(I,1).LT.YACT1(J))THEN
    P(I,3)=ZC1+M1*(P(I,1)-YC1)
    ELSE IF(P(I,1).LT.YACT2)THEN
    P(I,3)=ZACT1-(K1*SQRT(CY*C*(P(I,1)-YACT1(J))+18.))-2.)/(CZ*C)
    ELSE
    P(I,3)=ZACT2+M2*(P(I,1)-YACT2)
    END IF
290  IF(Y(L).GE.P(I,1))GOTO300
    L=L+1
    GOTO290
300  P(I,2)=Z(L-1)+(P(I,1)-Y(L-1))*(Z(L)-Z(L-1))/(Y(L)-Y(L-1))
C
C  SUM ABSOLUTE NET AREAS.
C
    AREA(1)=0.
    DY=DY/N
    DZ2=P(1,2)-P(1,3)
    ZSIGN2=1
    IF(DZ2.LT.0.)ZSIGN2=-1
C
C  ABSOLUTE AREA.
C
    DO 310 I=2,NINC
    DZ1=DZ2
    ZSIGN1=ZSIGN2
    DZ2=P(I,2)-P(I,3)
    ZSIGN2=1
    IF(DZ2.LT.0.)ZSIGN2=-1
    IF(ZSIGN2.EQ.ZSIGN1)THEN
    AREA(1)=AREA(1)+ABS((DZ2+DZ1)*DY)
    ELSE
    AREA(1)=AREA(1)+(DZ2**2+DZ1**2)*ABS(DY/(DZ2-DZ1))
    END IF
310  CONTINUE
    SAREA=AREA(1)/(2.*C3)
    K=SAREA*10.**5
    BAREA=K/10.
    PR=ABS(DAREA(J)/SAREA)
C
C  IF CHANGE DATUM IS OUTSIDE POST STORM
C  PROFILE. REQUEST A NEW DATUM2
C
311  IF(DATUM2.GE.ZC2.AND.DATUM2.LE.ZC1)GO TO 319
312  WRITE(6,315)
315  FORMAT(" CHANGE DATUM IS OUTSIDE THE LIMITS",/,
    $" OF THE POST STORM PROFILE.",/,
    $" ENTER NEW CHANGE DATUM")
    READ(5,*,ERR=312,END=410)DATUM2

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      GO TO 311
C
319 DO 320 I1=2,3
    AREA(I1)=0.
    POS(I1-1)=0.
    DZ2=P(I, I1)-DATUM2
    ZSIGN2=1
    IF (DZ2.LT.0.) ZSIGN2=-1
    IRODE=0
    DO 320 I=2, NINC
      DZ1=DZ2
      ZSIGN1=ZSIGN2
      DZ2=P(I, I1)-DATUM2
      ZSIGN2=1
      IF (DZ2.LT.0.) ZSIGN2=-1
      IF (ZSIGN2.EQ.ZSIGN1) THEN
        IF (ZSIGN1.EQ.1) AREA(I1)=AREA(I1)+(DZ2+DZ1)*DY
      ELSE IF (ZSIGN1.EQ.1) THEN
        AREA(I1)=AREA(I1)+DZ1**2*DY/(DZ1-DZ2)
      IF (IRODE.EQ.0) THEN
        POS(I1-1)=P(I-1, 1)+DY*DZ1/(DZ1-DZ2)
      IRODE=1
    ELSE
      END IF
    ELSE
      AREA(I1)=AREA(I1)+DZ2**2*DY/(DZ2-DZ1)
    END IF
320 CONTINUE
    EAREA=(AREA(3)-AREA(2))/C3
    DP=POS(2)-POS(1)
C
C   TOLERANCE, LOOP CHECK.
C
    IF (J.EQ.ML) GOTO 330
    IF (PR.LE.T2) GOTO 330
    GOTO 260
330   IP=2
    SAREA=-1.*SAREA
C
C   COMPUTE ADDITIONAL EROSION BASED ON STORM DURATION
C   SKIP COMPUTATION IF DUR = 0
C
    IF (DUR.EQ.0.) GO TO 335
    ADJ3=EAREA*DUR*.05+EAREA
    ADJ4=EAREA*DUR*.1+EAREA
    IF (ADJ3.GT.EAREA/2.) ADJ3=EAREA/2.
    IF (ADJ4.GT.EAREA/2.) ADJ4=EAREA/2.
C
335   IF (FLAG.EQ.1) WRITE(6, 1150)
      WRITE(6, 1140) SAREA, U2, U, EAREA, U2, U, DP, U, YACT1(J), U
      IF (DUR.GT.0.) WRITE(6, 1270) ADJ3, ADJ4, U2, U
      IF (FLAG.EQ.3) WRITE(6, 1130)
340   IF (QOUT.EQ.0) GOTO 360
350   WRITE(6, 1260)
      READ(5, 1030, ERR=350, END=410) ANSWER
      IF (ANSWER.EQ.'N') RETURN
      IF (ANSWER.EQ.'Y') GOTO 360
      GOTO 350
C
C   WRITE DATA INPUT/OUTPUT TO UNIT 14.
C
360   WRITE(14, 1160)
      WRITE(14, 1040) ILOC, IPROF, ISUR, IDATE
      WRITE(14, 1190) U, U
      DO 370 I=1, NPOINTS
370   WRITE(14, 1230) I, Y(I), Z(I)
      IF (REPLY.EQ.'Y') THEN
        WRITE(14, 1110) SURGE, U, DUR+5., HAVEHT, U, PDIA, TEMP, U4, FALLVEL, U,
          *DATUM, U, DATUM2, U
      ELSE
        WRITE(14, 1100) SURGE, U, DUR+5., HAVEHT, U, FALLVEL, U, DATUM, U,

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$DATUM2,U
END IF
IF (FLAG.NE.2)GOTO380
WRITE(14,1120)
WRITE(14,FRMT)
RETURN
380 WRITE(14,1170)
WRITE(14,1140)SAREA,U2,U,EAREA,U2,U,DP,U,YACT1(J),U
IF(DUR.GT.0)WRITE(14,1270)ADJ3,ADJ4,U2,U
C
C C
C COMPUTE AND WRITE PREDICTED PROFILE AT 10 FOOT/METER INTERVALS.
YS1=YACT1(J)/10.
YE1=YACT2/10.
IF (YS1.EQ.0.AND.YC1.LT.0.)GOTO390
IF(YS1.GE.0)YS1=YS1+1
390 YS2=YS1*10
YE2=YE1*10
WRITE(14,1180)U,U
WRITE(14,1210)YC1,ZC1
WRITE(14,1210)YACT1(J),ZACT1
DO 400 IY=YS2,YE2,10
YI=IY
ZI=ZACT1-(K1*SQRT(CY*C*(YI-YACT1(J))+18.))-2.)/(CZ*C)
400 WRITE(14,1210)YI,ZI
WRITE(14,1210)YACT2,ZACT2
WRITE(14,1210)YC2,ZC2
IF(FLAG.EQ.1)WRITE(14,1150)
WRITE(14,1200)
WRITE(14,1050)(YACT1(J+1-M),M=1,J)
WRITE(14,1050)(DAREA(J+1-M),M=1,J)
IF(FLAG.EQ.3)WRITE(14,1130)T1,DAREA(J),T2,PR
WRITE(14,1220)
1000 FORMAT("ENTER - SURGE DATUM, SURGE HEIGHT, WAVE HEIGHT,"/,
$ BX,"AND CHANGE DATUM (IN",1X,A2,")",//)
1010 FORMAT("ENTER - MEDIAN SAND SIZE (MM) AND WATER TEMP. (DEG",
$ A2,"")
1015 FORMAT("ENTER - FALL VELOCITY")
1020 FORMAT("COMPUTE PARTICLE FALL VELOCITY GIVEN DIAMETER?",
$ " - Y OR N")
1030 FORMAT(A1)
1040 FORMAT(" LOCATION "A4," PROFILE NO.",19,/,
$ "SURVEY NO.",15," DATE (YYMMDD)",16,/)
1050 FORMAT(1X,13F10.3)
1060 FORMAT(" END POINT OF PROFILE IS ABOVE SURGE LEVEL")
1070 FORMAT(" SURGE LEVEL ABOVE PROFILE")
1080 FORMAT(" PREDICTED CURVE INTERCEPT TO THE LEFT OF PROFILE")
1090 FORMAT(" PREDICTED CURVE INTERCEPT TO THE RIGHT OF PROFILE")
1100 FORMAT(//," SURGE HEIGHT = ",F6.2,1X,A2,/,
$ " SURGE DURATION = ",F6.2," HRS",/,
$ " SIGNIFICANT WAVE HEIGHT = ",F6.2,1X,A2,/,
$ " MEDIAN PARTICLE FALL VELOCITY = ",F6.4,1X,A2,"/SEC",/,
$ " SURGE DATUM = ",F6.2,1X,A2,/,
$ " CHANGE DATUM = ",F6.2,1X,A2)
1110 FORMAT(//," SURGE HEIGHT = ",F6.2,1X,A2,/,
$ " SURGE DURATION = ",F6.2," HRS",/,
$ " SIGNIFICANT WAVE HEIGHT = ",F6.2,1X,A2,/,
$ " MEDIAN SEDIMENT DIAMETER = ",F6.2," MM",/,
$ " WATER TEMPERATURE = ",F6.1,1X,"DEG",A2,/,
$ " COMPUTED FALL VELOCITY = ",F6.4,1X,A2,"/SEC",/,
$ " SURGE DATUM = ",F6.2,1X,A2,/,
$ " CHANGE DATUM = ",F6.2,1X,A2)
1120 FORMAT(" DATA INPUT ERROR - CHANGE SURGE HEIGHT",/,
$ " PROFILE LIMITS OR CHECK COORDINATES OF DATA")
1130 FORMAT(" WARNING - SOLUTION DID NOT MEET CONVERGENCE CRITERIA",/,
$ " AREA TOLERANCE = ",F6.3," NET AREA = ",F6.3,/,
$ " RELATIVE TOLERANCE = ",F6.3," RELATIVE ERROR = ",F6.3)
1140 FORMAT(//," TOTAL EROSION (AE) = ",F8.1,1X,A2,"3/",1X,A2,/,
$ " ABOVE DATUM CHANGE (AS) = ",F8.1,1X,A2,"3/",
$ 1X,A2,/,
$ " HORIZONTAL SHIFT OF CHANGE DATUM = ",F8.1,1X,A2,/.

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      $      " POSITION OF SURGE LEVEL = " F8.1,1X,A2,/)
1150  FORMAT(" WARNING - PORTION OF PREDICTED PROFILE ABOVE/BELOW",/,
      $      " PRESTORM PROFILE WHERE REVERSE TREND SHOULD OCCUR")
1160  FORMAT(//,5X,"DUTCH STORM EROSION PREDICTION",/)
1170  FORMAT(//,16X,"*** RESULTS ***",/)
1180  FORMAT(" POST-STORM PROFILE ",/,
      $      " DISTANCE ELEVATION",/,7X,A2,9X,A2,/)
1190  FORMAT(//,10X,"*** INPUT ***",/,
      $      " PRE-STORM PROFILE ",/,
      $      " POINT DISTANCE ELEVATION" /, "NUMBER",7X,A2,9X,A2,/)
1200  FORMAT(//,"SURGE POSITION AND NET AREA ITERATIONS IN",/,
      $      " REVERSE ORDER (FROM LAST TO FIRST).",/)
1210  FORMAT(1X,F9.1,2X,F10.2)
1220  FORMAT(//,/)
1230  FORMAT(14,2X,F9.1,2X,F10.2)
1240  FORMAT("SURGE, WAVE HEIGHT OR FALL VELOCITY BELOW",/,
      $      " MINIMUM ACCEPTABLE, RE-ENTER DATA")
1250  FORMAT("TEMPERATURE NOT ACCEPTABLE, RE-ENTER DATA")
1260  FORMAT("OUTPUT RESULTS TO FILE OR LINE PRINTER? - Y OR N")
1270  FORMAT(//,1X,"ESTIMATED EROSION ADJUSTED FOR",
      $      " DURATION",/,5X,"(IF SUFFICIENT MATERIAL EXISTS)",/,
      $      "/,1X,"EROSION ABOVE CHANGE DATUM (AS) = FROM",F8.2,
      $      " TO ",F8.2,1X,A2,"J/",A2,/)
      RETURN
410  CLOSE(5)
      OPEN(5,FILE='INPUT')
      RETURN
      END

C
C*****
C
      SUBROUTINE SPEED
      REAL PDIA,CTEMP,FALLVEL,RHOSED,RHOSEA,KVCSEA,MU,RHO,KVC,GRNBUDY,R
      COMMON /FALLVEL,PDIA,CTEMP,FALLVEL,SURGE,WAVEHT,TEMP,BAREA
      DATA RHOSED,RHOSEA,KVCSEA/2.70,1.027,1.048/

C
C      GIVEN MEDIAN PARTICLE DIAMETER (IN MM) AND WATER TEMPERATURE
C      (IN DEG. C) 'SPEED' COMPUTES THE PARTICLE FALL VELOCITY
C      (IN METERS/SECOND). PROGRAM ASSUMES SEDIMENT DENSITY
C      (RHOSED = 2.70 GM/CM. CM), AMBIENT WATER DENSITY RATIO
C      (SALTWATER, 33 PPT - RHOSEA = 1.027) AND AMBIENT WATER
C      VISCOSITY RATIO (KVCSEA = 1.048). REFER TO CETN-II-4
C      FOR FURTHER INFORMATION.
C
      MU=.0020319+.015883/EXP(CTEMP*.9/22.)
      RHO=RHOSEA*(1-.000019547*ADS(CTEMP*.4)**1.68)
      KVC=KVCSEA*MU/RHO
      GRNBUDY=.9806*(RHOSED-RHO)*PDIA**3/(RHO*KVC**2)
      R=KVC/PDIA
      IF (GRNBUDY.LT.39.) THEN
        FALLVEL=GRNBUDY*R/180.
      ELSE IF (GRNBUDY.LE.10000.) THEN
        FALLVEL=GRNBUDY**.7*R/60.
      ELSE
        FALLVEL=SQRT(GRNBUDY)*R/9.54
      END IF
      RETURN
      END

C
C*****
C
      SUBROUTINE EXPLAIN
C
C      THIS SUBROUTINE EXPLAINS THE VARIABLES USED BY THE PREDICT
C      PROCEDURE.
C
      COMMON/BLK/IDATE,ITIME,IPOF,ILOC,ISUR,DIST,IUNIT
C
C      DETERMINE IF WATER TEMP TO BE INPUT IN DEGREES C. OR F.
C
      ITEMP=1HF

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      IF(IUNIT.EQ.2HM)ITEMP=1HC
C
      WRITE(6,100)IUNIT,IUNIT,IUNIT
100  FORMAT(1X,/,5X,"THE PROCEDURE REQUIRES THE",
      $ " FOLLOWING INPUT",/,
      $X,"-----",//,
      $2X,"SURGE DATUM - THE VERTICAL DATUM USED TO COMPUTE THE SURGE"
      $ /,8X,"LEVEL (IN ".A2." RELATIVE TO THE PROFILE DATA)",//,
      $2X,"SURGE HEIGHT - SURGE HEIGHT ABOVE",
      $ " THE SURGE DATUM (IN ".A2."),",//,
      $2X,"WAVE HEIGHT - SIGNIFICANT DEEPWATER WAVE HEIGHT ",
      $ "(IN ".A2."),",//)
C
      WRITE(6,110)IUNIT,ITEMP,IUNIT
110  FORMAT(
      $2X,"CHANGE DATUM - VERTICAL DATUM, (IN ".A2.
      $ " RELATIVE TO THE PROFILE DATA)",/,
      $8X," ABOVE WHICH THE ERODED AREA WILL BE COMPUTED",//,
      $2X,"MEDIAN SAND SIZE - ALWAYS IN MM.",//,
      $2X,"WATER TEMPERATURE - IN DEGREES ".A1,//,
      $2X,"FALL VELOCITY - IN ".A2,"/SEC. (OPTIONAL, "
      $ "PROGRAM WILL COMPUTE THIS)",//)
      WRITE(6,115)
115  FORMAT(2X,"STORM DURATION - HOURS SURGE EXCEEDED A LEVEL"/,
      $8X,"3.3 FT (1 M) LESS THAN THE PEAK SURGE.",//)
C
      WRITE(6,117)
117  FORMAT("CONTINUE?")
      READ(5,118,END=135,ERR=135)IREPLY
118  FORMAT(1A1)
      IF(IREPLY.NE.1HY)GOTO140
C
      WRITE(6,120)
120  FORMAT(/,5X,"THE PROGRAM OUTPUTS THE FOLLOWING",/,
      $5X,"-----",//,
      $2X,"TOTAL EROSION (AE)- THIS IS THE VOLUME OF THE",/
      $,2X," TOTAL ERODED AREA, REGARDLESS OF DATUM",//,
      $2X,"ABOVE DATUM CHANGE (AS) - THIS IS THE VOLUME",/,
      $2X," CHANGE ABOVE THE CHANGE DATUM.",//,
      $2X,"HORIZONTAL SHIFT - THIS IS THE HORIZONTAL",/,
      $2X," SHIFT OF THE CHANGE DATUM",
      $ " INTERCEPT",//,
      $2X,"POSITION OF THE SURGE INTERCEPT - THE POSITION.",/,
      $2X," RELATIVE TO THE SURVEY DATA, OF THE",/,
      $2X," POST-STORM SURGE LEVEL INTERCEPT.",//)
C
      WRITE(6,130)
130  FORMAT(2X,"ADJUSTED EROSION AMOUNTS - THIS IS THE RANGE OF",/,
      $8X,"-AS- ADJUSTED FOR THE DURATION OF THE STORM (AS DEFINED",/,8X,
      $ "ABOVE). MAXIMUM ALLOWED ADJUSTMENT IS 50 PERCENT OF -AS-",//)
140  RETURN
135  K7=EOF(5)
      RETURN
      END

```

APPENDIX B: NOTATION

A_e	Volume of erosion and accretion zones computed between prestorm and poststorm profiles ($1/2 A_g$)
A_g	Gross change between prestorm and poststorm profiles
A_{msl}	Volume of material eroded above mean sea level (msl)
A_s	Volume of material removed above the surge level
D_{50}	Median sediment size
H_{os}	Significant deepwater wave height
L_o	Significant deepwater wave length
m_1	Predicted poststorm dune slope
m_2	Seaward slope of the poststorm profile
R	Maximum shoreward extent of poststorm profile/surge level intercept
S	Peak surge level relative to mean sea level
t	Water temperature during storm event
w	Fall velocity of median sediment size, D_{50}
x	Horizontal position, positive in seaward direction
y	Vertical position, positive with increasing elevation
σ_{A_s}	Standard deviation of prediction of A_s

END

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